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EROSION OF A THREE-STAGE POTASSIUM TURBINE

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Abstract

The NASA technology effort on potassium vapor turbines began in 1961. Initially, a two-stage turbine was tested for 5000 hours with a vapor exit quality of about 92 percent. A recently completed 5000-hour endurance test with a three-stage turbine extended this experience to a vapor exit quality of about 87 percent, comparable to current nuclear steam plant practice.

Turbine rotor blade overall damage was small and indicated a potential life many times the actual 5000 hours of testing. The third-stage inlet vapor quality during the initial 4300 hours of testing was 93 percent or less (91 percent) and the exit quality was 87 percent or less for the same period. The Rene' 77 third-stage rotor blades experienced an average weight loss of 0.046 gram corresponding to a volume loss of 0.005 cm^3. Material removal occurred only at the leading edge. The maximum removal noted was approximately 2 mils near the dovetail platform extending to about 11 mils near the top of the leading edge to about 27 mils within the last 1 percent of the airfoil height. Impact damage is visible at the blade tip.

Material removal from the molybdenum-base TZM and TZC third-stage rotor blades was atypical and is attributed mainly to corrosion from the oxygen contamination of the potassium system. Material loss occurred at the leading edges, suction surfaces, and trailing edges of the blades. The material removal from the leading edges tended to be an almost uniform 21 mils from the dovetail platform toward the blade tip. At about 60 mils from the tip (95 percent of airfoil height), the leading edge profile receded a maximum of 59 mils. The weight loss experienced by a typical TZM and TZC blade was 0.913 and 0.905 gram, respectively, corresponding to volume losses of 0.090 and 0.089 cm^3, respectively.

Since the Rene' 77 is known to be less resistant to erosion than TZM and the molybdenum damage is predominately due to corrosion, the lack of significant material removal from the Rene' 77 is considered representative of the endurance capability of a potassium turbine with 87 percent exit vapor quality.

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Introduction

The potassium Rankine-cycle power generating system is suitable for providing multi-hundred kilowatts of electric power for space systems. Research and technology for this system are supported by NASA. As a guide to recent technological efforts, a nominal 300 kWe reference potassium Rankine system was established (Ref. 1). A simplified schematic is presented in Fig. 1.

This reference system assumes the use of turbine interspool and interstage condensate removal devices to maintain exit vapor quality at 89 percent or higher. The 89 percent vapor quality, although somewhat arbitrary, is consistent with steam turbine experience which associates substantial material removal with operation at lower quality levels. Material removal is generally attributed to droplet impact damage and to solubility of the material in the working fluid.

Initial efforts in 1961 were directed at the development of a two-stage turbine. The turbine was successfully tested for 2000 hours at 1500° F turbine inlet temperature, 18,250 rpm and a vapor quality of 96 percent at the second stage inlet (Table I). After posttest inspection of the turbine, specimen rotor blades were replaced and 3000 hours of additional testing was added. The two stage turbine rotor blades exhibited negligible weight loss (Table II) and no impact damage. Its success prompted the development of a three stage turbine for exploration of even lower vapor quality.

Test Turbine

The fluid dynamics and mechanical design of the three-stage (Fig. 2) turbine were predicated upon the two-stage turbine experience. The turbine was designed for operation at inlet vapor temperature of 1450° and 1550° F and for a 15,000-hour life at an inlet vapor temperature of 1550° F and rotational speed of 18,250 rpm (Table III). The design life required the use of TZM for the first and second stage wheels. Shrouded blades were introduced to increase turbine efficiency (and, hence, moisture level) and to assist in removing liquid potassium from the blades as would be required by a follow-on condensate removal program now underway. Table IV compares the materials used for the two- and three-stage turbines. Note that U-700, Rene' 77 and Astroloy are essentially the same material with small differences in composition to control an embrittling sigma phase.

The three stage turbine follows the materials selection concept of the two stage turbine by utilizing mainly rotor blades of a nickel-base alloy Rene' 77, and a limited number of molybdenum base TZM and TZC alloys which are candidates for the potassium high temperature turbine. The candidacy of these materials, particularly TZM, is advanced by such documentation as Ref. 4, describing the extremely low weight loss experienced by TZM in potassium at 2000° F, and Ref. 5 which identifies the cavitation resistance of TZM as exceeding that of Rene' 77. Four TZM and four TZC blades are installed in the second-stage rotor and another set are in the third-stage rotor. The blades are paired 90° apart. Opposite pairs are of the same materials - TZM or TZC.

Early experience with the three stage turbine led to the following modifications:

1. Installation of a viewing port (Fig. 3) to permit periodic visual inspection of the third-stage rotor when the turbine is shut down. A 0.4 inch diameter boroscope was a visual aid. Photographs could be taken through the boroscope. The intent was to ensure that some blade wear data were available even if the turbine was damaged near the end of the test. A secondary objective was to determine the test time when blade wear would be initiated and to observe this pattern of wear with time. Further, it was hoped that an incipient turbine failure might be detected by periodic inspection.

2. New TZM blades were fabricated from cross-rolled bar stock with a more randomly oriented grain structure than the prior test blade material. This precluded splintering along the fibrous structure observed with material previously used for blading.

3. The third stage rotor blades were deshrouded to permit a better view of the blade tips through the view port. This did not reduce the inlet vapor quality to the third stage.

Test Facility

The principal features of the test facility are shown in Fig. 5. The potassium boiler is gas fired. Heating is predominantly by radiation to the risers. The upper boiler drum and the downcomers are insulated from direct radiation.

A zirconium hot trap is located at the end of the boiler not shown in Fig. 4. The function of the zirconium is to remove oxygen in the boiler. Another zirconium trap is located in the condenser.

The boiler, valves, turbine casing, condenser, pump, and piping were fabricated from 316 stainless steel. The boiler was designed for operation at a maximum temperature of 1600° F.

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Test History

Initially periodic inspection of the third-stage rotor blades was planned after every 500 hours of endurance testing. Pragmatically, the first inspection took place after 405 hours while a facility leak was being repaired. The second inspection at 1000 hours was planned as was the third inspection at 1865 hours. The extension of the time period between inspections reflected the excellent appearance of the blades at the 1000-hour inspection. Subsequent inspections were conducted when facility leaks resulted in an extended shutdown. The test history is presented by Fig. 5.

Although the leading edges of the rotor blades exhibited little damage, material deposits began to accumulate on stator and rotor blades. At the first shutdown, the characteristic deposits were thin and adherent and composed of iron-nickel-molybdenum from the 316 stainless steel facility. At the 1000-hour inspection and subsequent inspections, a bulky deposit determined to be potassium zirconate ($K_2O.2ZrO_2$) was observed, the zirconium sources being the boiler and the condenser oxygen gettering traps. The reduced flow and torque experienced after the first shutdown (Fig. 6) are attributed to these deposits. Posttest effective area flow tests of the nozzle diaphragms confirmed blockage caused by the deposits.

At approximately 750 test hours, the flow rate began to increase and eventually leveled off at a value greater than the initial flow rate. Flow bypassing of a nozzle diaphragms was suspected, but the location could not be determined. At shutdown, a hole in the bullet nose was found which did permit flow to bypass the first stage nozzle.

Each shutdown, whether planned or due to facility leaks, resulted in an increase in the oxygen content of the potassium despite internal pressurization of the facility with argon. Figures 7 and 8 show the apparent oxygen concentration as indicated by an oxygen meter in the boiler feed EM pump bypass. Indicated on the figures are oxygen analyses, by the amalgamation method, performed on potassium sampled from the condenser bowl and the pump bypass. The presence of oxygen is germane to the evaluation of test results.

Test Results and Evaluation

Rotor Blades

To establish third-stage rotor blade wear, all blades were weighed prior to testing and again after testing. Leading edge profile measurements of six reference blades (2 each TZM, TZC, and Rene' 77) were taken before and after testing. Selected blades were pantascribed before and after testing. The reference blades were examined after testing.

Material removal from the molybdenum blades substantially exceeded that from the Rene' 77 hardware. This was evidenced by the weight change of the reference blades (Table V) and by the change in leading edge profile (Fig. 9).

About half the rotor blades were initially washed and weighed, then about half of these blades were vapor honed and reweighed. The typical Rene' 77 blade exhibited a weight gain, primarily due to deposits of potassium zirconate, at the initial weighing. Removal of most of these deposits resulted in an average net weight loss of 0.046 gram or 0.24 percent of the airfoil calculated weight. The molybdenum blades exhibited an initial loss of about 0.8 gram which increased to over 0.9 gram after vapor honing. The weight loss represents about 3 to 4 percent of the airfoil calculated weight.

Material removal as indicated by the change in the leading profile was greater for the molybdenum blades (Fig. 9). These blades exhibit a rather uniform loss in profile of about 21 mils, near the base of the airfoil outward toward the tip. At about 60 mils from the tip of the blade (about 95 percent of the blade height) loss of material increased at a substantial rate to about 59 mils at the tip. In contrast the Rene' 77 exhibited little material removal from the leading edge near the base of the airfoil (about 1 to 2 mils). The material removed increased with the radial distance along the leading edge, suggesting a velocity dependence unlike the uniformity measured for molybdenum blades. The material removal strongly increased at about 99 percent of the airfoil height to a maximum of 27 mils at the tip. A third Rene' 77 blade profile (not shown on Fig. 9) was similar to that of blade No. 71, which exhibited 2 mils wear at about 88 percent of airfoil height compared to the 11 mils of blade No. 4.

Pantascribe measurements of reference rotor blade profile dimensions at identical positions before and after testing (Figs. 10 and 11) show at most a slight increase in dimensions of the Rene' 77 blades due to adherent deposits and a somewhat uniform decrease in dimensions of the wetted suction side of the molybdenum blades despite deposits. The uniform reduction along the wetted suction surface is suggestive of chemical attack.

Metallurgical inspection of the blades supports the view that the molybdenum blades were subject to chemical attack. A typical view (Figs. 12 and 13) indicates that the expected impact damage at the tip of the molybdenum blades is barely visible except at high magnifications and typical impact wormholes are not deep. Impact damage cracks can be seen at the bottom of the holes. In contrast, Fig. 15 shows well-defined worm-holing of a Rene' 77 blade tip. Impact damage at the bottom of the hole is well defined. Damage to the leading edge of the molybdenum blades shows radial grooving attributable to corrosion and not the worm-holing of impact damage (Fig. 15). The Rene' 77 blades also do not show impact damage on the leading edges.

The accelerated material loss from the molybdenum alloys during the endurance test is apparent from Table VI which presents the weight changes of the first and second stages of both the two stage and three stage turbine after 5000 hours of endurance testing. The data show that the second stage molybdenum blades of the three stage turbine exhibited a weight loss 30 to 40 times greater than comparable blades of the two stage turbine.

In summary, the data indicates almost no material was removed from the Rene' 77 blades over the 5000 endurance test hours with the blade tips being the principal removal site. Tip damage is obviously due to impact. The material removal from the molybdenum blades was much greater. Its rather uniform character along wetted surfaces suggests chemical attack. The history of the test supports the presence of oxygen as the contributor to chemical attack. Impact damage at the blade tips is barely discernable.

Vapor Quality

The hole in the bullet nose and the flow blockage caused by deposition of potassium zirconate altered the vapor quality throughout the test. Posttest measurements of nozzle diaphragm effective area and the flow bypass through the bullet nose were correlated with temperature (Fig. 16), torque, and flow data to ascertain the calculated vapor quality at the inlet to the third-stage rotor. The results (Fig. 17) show the design vapor quality of about 91 percent was obtained during the first 700 test hours, then slowly increased to 93 percent until about the 4300 test hour, then increased to 95 percent for the remainder of the test. The predominant quality was about 93 percent.

Viewport

The viewport was proven to be useful in following the onset of erosion damage at the rotor blade tips by boroscope examination and photography and in observation and sampling of the deposits. The erosion damage was first noted at the third (1865-hour) inspection. The potassium zirconate was found initially at the 1000-hour inspection. Molybdenum blade corrosion was evident at the first (405-hour) inspection. The photographs (Figs. 18 to 21) do not reproduce the clarity of the view.

Turbine Performance

Performance data was taken during the normal heatup of the system. The analytical pretest performance prediction agrees with the test data (Fig. 22). The posttest performance calculations do not agree as well (Fig. 23).

Conclusions

The three-stage turbine 5000-hour endurance test demonstrated that the nickel-base alloy Rene' 77 resists erosion at quality levels comparable to levels assumed in the reference potassium Rankine cycle. The greater material removal observed on the candidate molybdenum base alloys of TZM and TZC is attributed to chemical attack by oxygen containing potassium. (Other investigators have shown that the impact resistance of TZM exceeds Rene' 77 and that TZM does not corrode in oxygen-free potassium in a refractory system with high-purity potassium.)

The viewport was successfully utilized for determining

the onset of visible wear. By coordinating the viewing with facility outages, the extra time involved in inspection was minimized.

The endurance test demonstrated that the problems experienced in prior testing had been resolved, that the performance calculation methods are well established, and that low vapor quality can be resisted by the candidate materials. The next step appears to be development of a full scale potassium turbine for the reference cycle.

References

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8. Material Specification B50T56-S1, Aircraft Gas Turbine Division, General Electric Company, Evendale, Ohio.

TABLE I. - TWO-STAGE TURBINE TEST CONDITIONS[a]

Speed, rpm	18,250
Weight flow, pps	1.8
Inlet vapor temperature, °F	1500
Pressure ratio, total to static	3.5
Inlet vapor quality, Stage 1, percent	99
Inlet vapor quality, Stage 2, percent	96

[a]Source: Ref. 2.

TABLE II. - AVERAGE BLADE WEIGHT LOSS AFTER 5000-HOUR ENDURANCE TEST[a]

Material	Average weight loss after vapor honing, gram
First stage	
U-700	-0.073
Second stage	
U-700	[b]-0.001
TZM	-0.040
TZC	-0.038

[a]Weight loss after 2000 hours exceeded weight loss after additional 3000 hours by factors of 2 to 4.
[b]Weight gain of 0.003 gram after 3000 hour test.

TABLE III. - THREE-STAGE TURBINE DESIGN REQUIREMENTS AND TEST CONDITIONS[a]

	Design	Test
Speed, rpm	18,250	18,250
Inlet vapor temperature, °F	1450 to 1550	1500
Third stage inlet vapor quality, percent	90 to 92	[b]91
Exit pressure, minimum, psia	2	2.5
Pressure ratio	3.6 to 15.5	9.7
Design life hours at 1550° F, 18,250 rpm	15,000	5000 (planned endurance)

[a]Ref. 7.
[b]During initial 405 hours of test.

TABLE IV. - TEST TURBINE MATERIALS

	Three stage[b]	Two stage[a]
Casing, bullet nose, scroll	316 ss	316 ss
Rotor disc		
Stage 1	TZM	Astroloy
Stage 2	TZM	Astroloy
Stage 3	Astroloy (modified)	
Rotor blades		
Stage 1	Rene' 77 (cast)	U-700 Wrought
Stage 2	Rene' 77 (cast) TZM (4) TZC (4)[a]	U-700 Wrought TZM (4) TZC (4)
Stage 3	Rene' 77 (cast) TZM (4) TZC (4)[a]	
Blade retainers (all stages)	Rene' 41 Wrought	Rene' 41 Wrought
Shaft	A-286	A-286
Tie bolt	U-700 Wrought	U-700 Wrought
Stator blades (all stages)	L-605	L-605
Stator blade braze	H-33[c]	H-33[c]

[a]Ref. 6.
[b]Ref. 7.
[c]Ref. 8.

TABLE V. - THIRD-STAGE ROTOR BLADE POSTTEST WEIGHT AND VOLUME CHANGES

Material	Blade No.	Initial weight, gram	Weight change		Volume change,[a] cm^3
			After washing, gram	After washing and vapor honing, gram	
Rene' 77	Typical (#75)	28.859	0.113	-0.026	0.003
	Average	27.874	0.115	-0.042	.005
TZM	Typical (#BB)	36.320	-0.792	-0.913	.090
	Average	36.174	-0.840	-0.944	.092
TZC	Typical (#W)	36.491	-0.833	-0.925	.091
	Average	36.164	-0.817	-0.905	.089

[a]Volume change after washing and vapor honing.

Note: Calculated weight, gram:

	Airfoil	Blade
Rene' 77	19.12	29.89
TZM/TZC	24.66	38.42

TABLE VI. - COMPARISON OF TWO STAGE TURBINE AND THREE STAGE TURBINE BLADE AVERAGE WEIGHT CHANGES

Blade material	Average weight change, gram	
	Two stage turbine	Three stage turbine
First stage rotor		
U-700	-0.073	
Rene' 77		-0.005
Second stage rotor		
U-700	0.001	
Rene' 77		0.027
TZM	-0.040	-1.659
TZC	-0.038	-1.105
Third stage rotor		
Rene' 77		-0.042
TZM		-0.944
TZC		-0.925

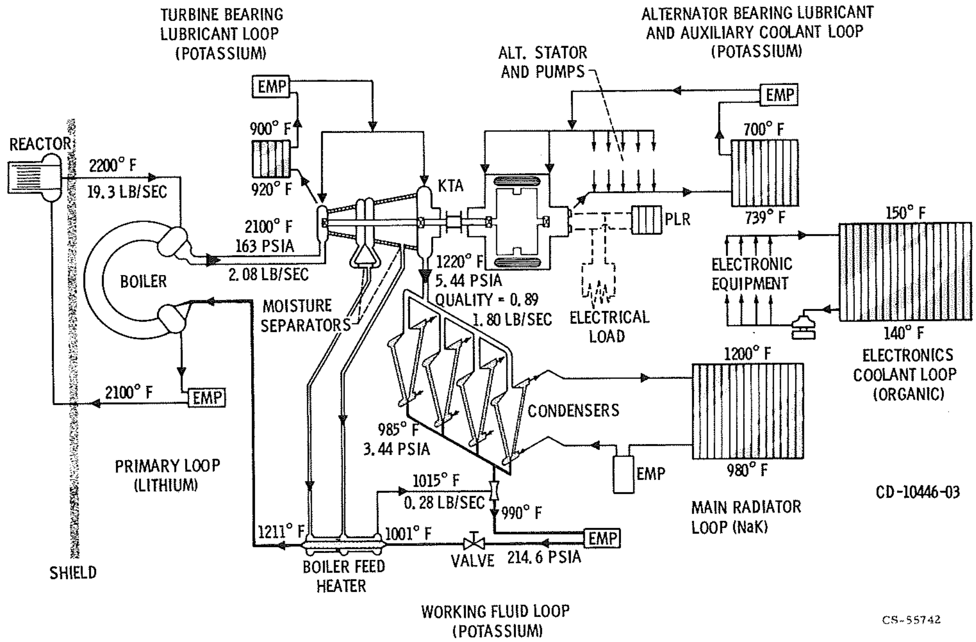

Figure 1. - Advanced Rankine power system (nominal 300 kW_e).

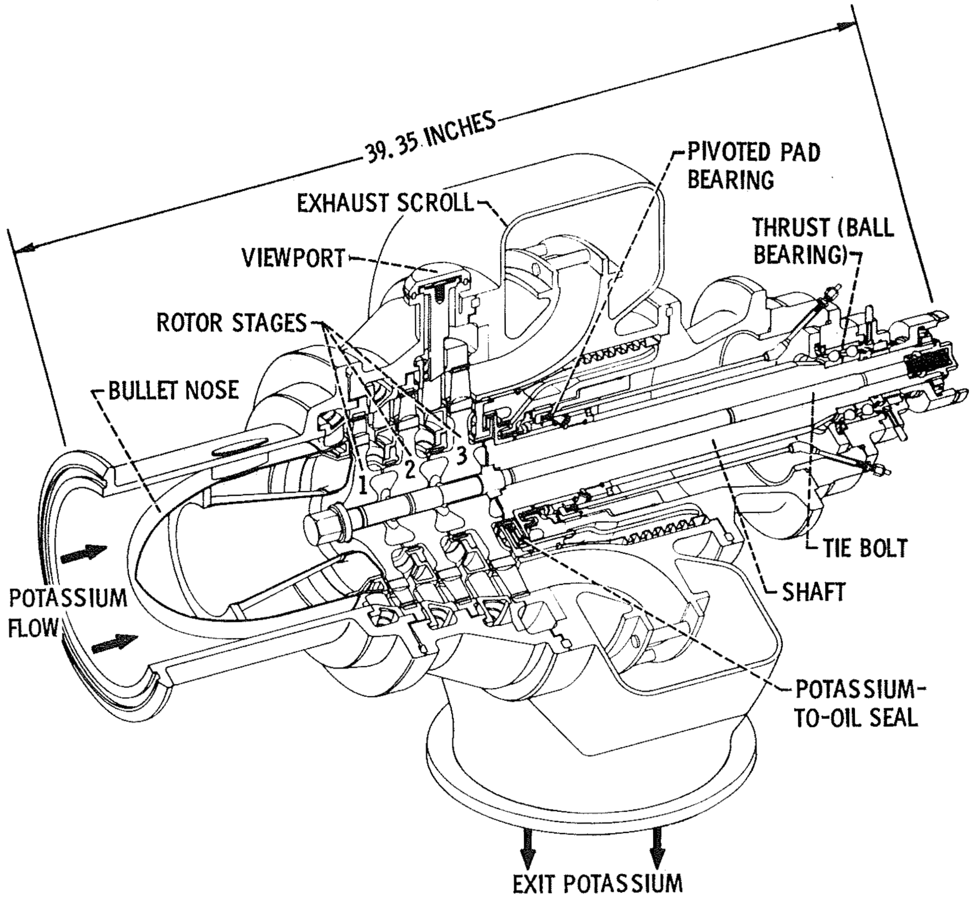

Figure 2. - Three stage potassium test turbine-5000 hour test.

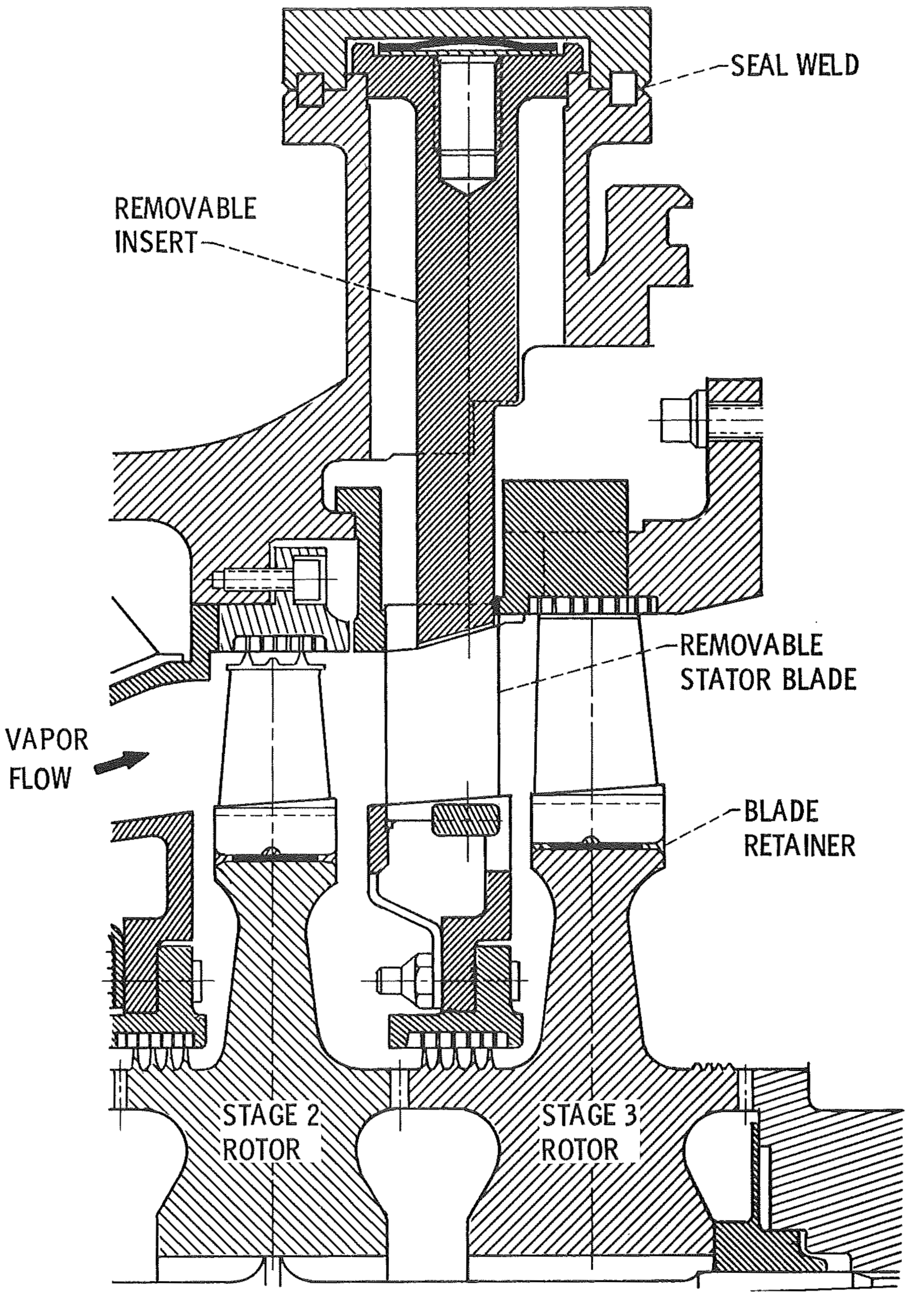

Figure 3. - Stage three rotor blade viewport.

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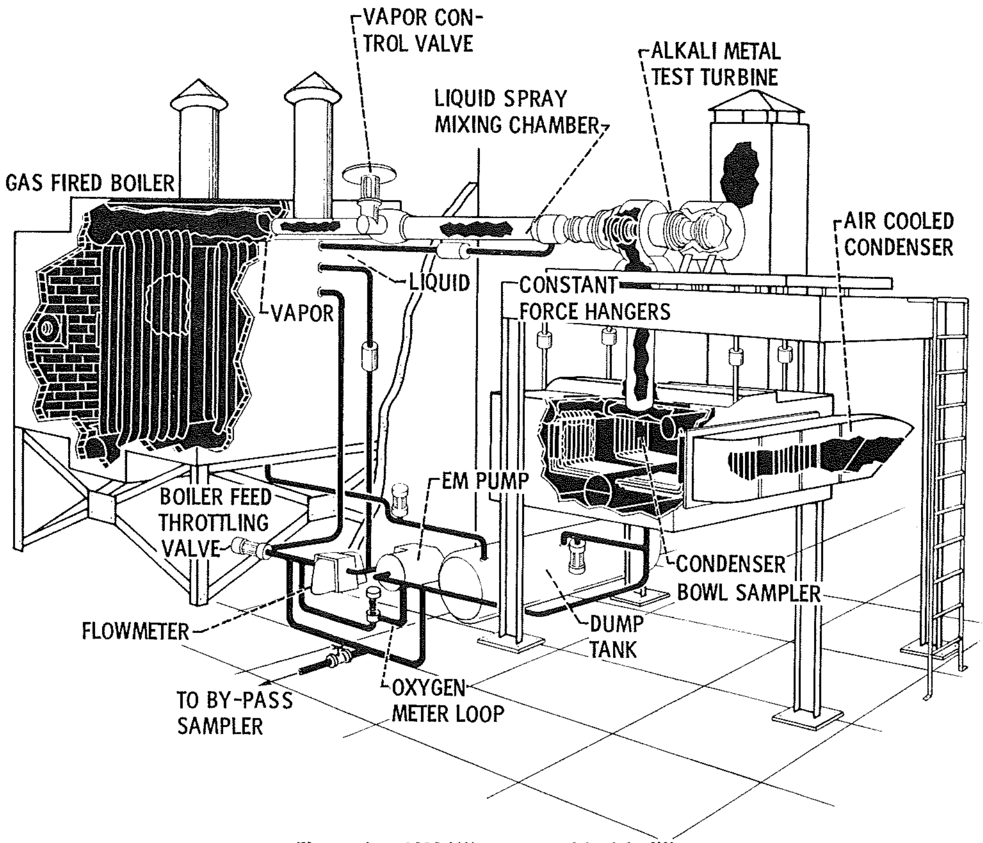

Figure 4. - 3000 kW component test facility.

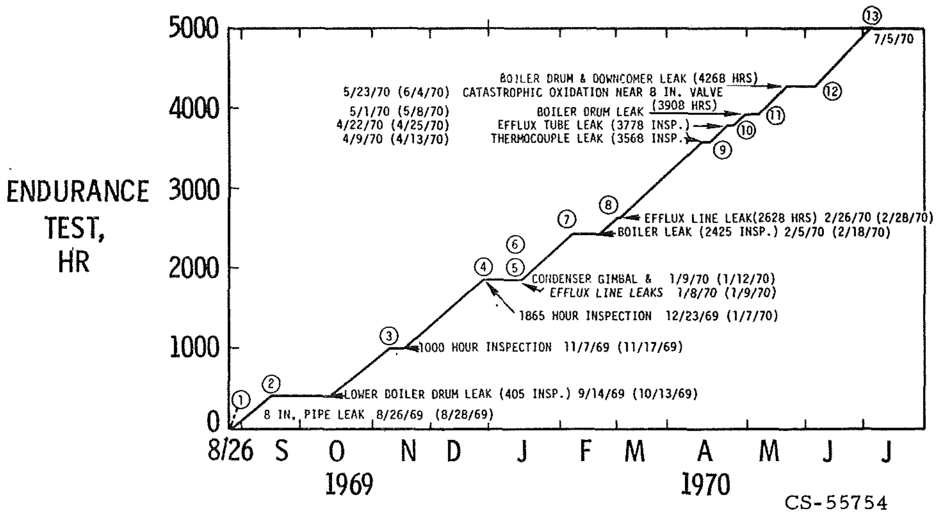

Figure 5. - Three stage potassium turbine accumulated endurance test hours versus time.

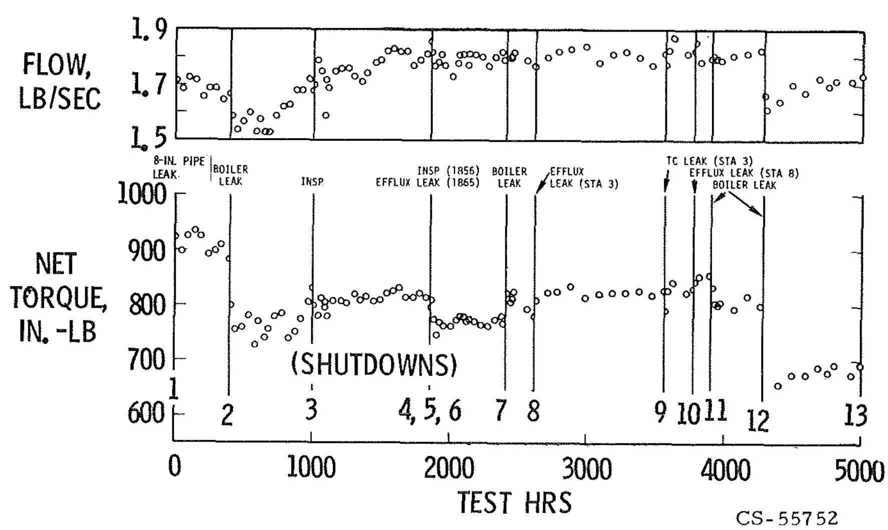

Figure 6. - Endurance test performance. Inlet temperature, 1500^0 F; speed, 18 250 rpm.

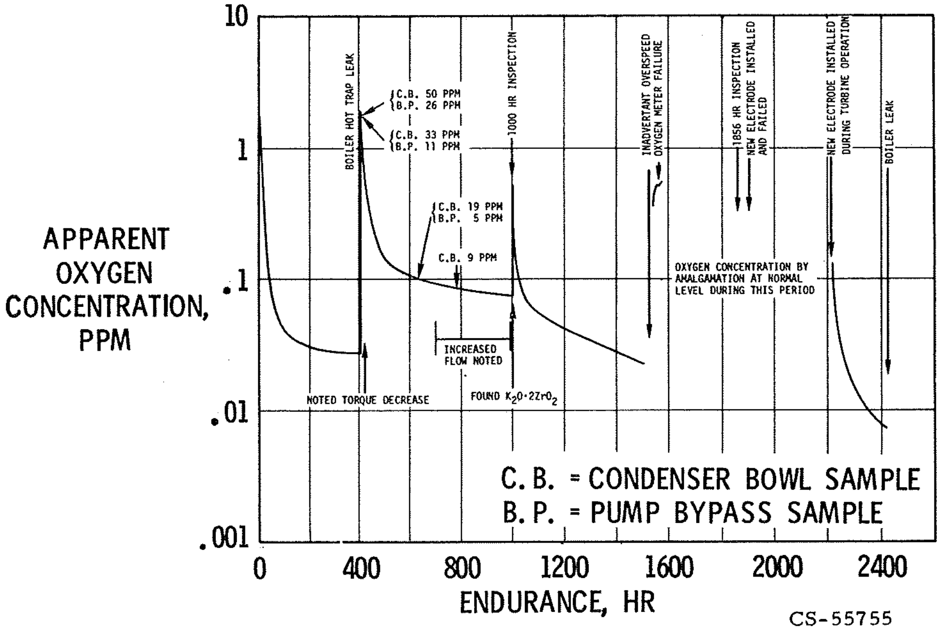

Figure 7. - Three-stage turbine oxygen meter data.

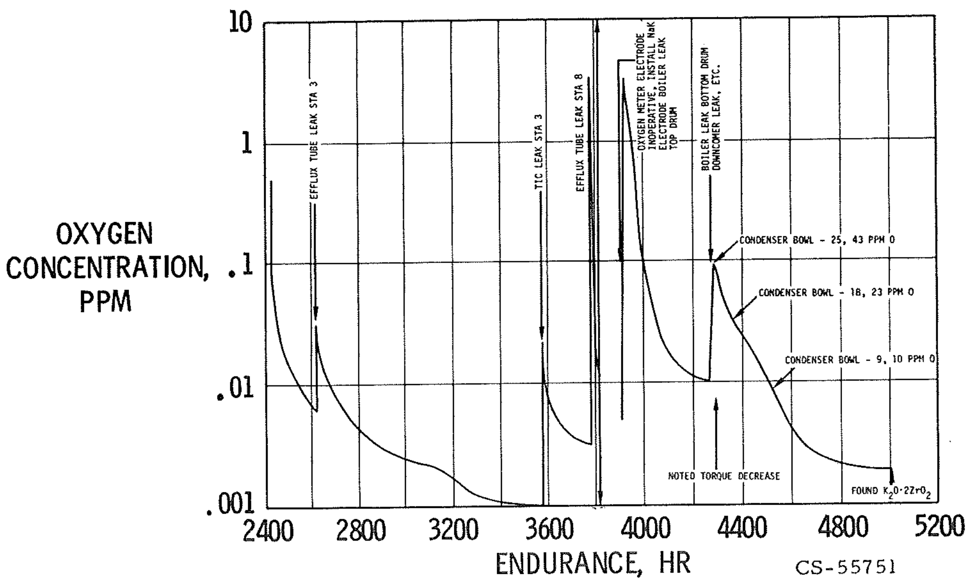

Figure 8. - Three-stage turbine oxygen meter data.

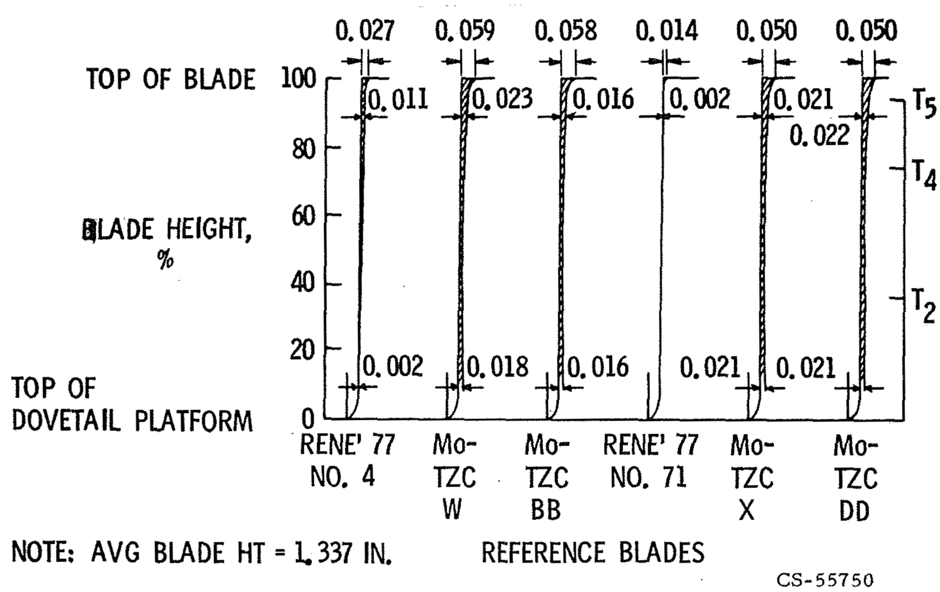

Figure 9. - Three stage K turbine surface plate measurements of bucket leading edges.

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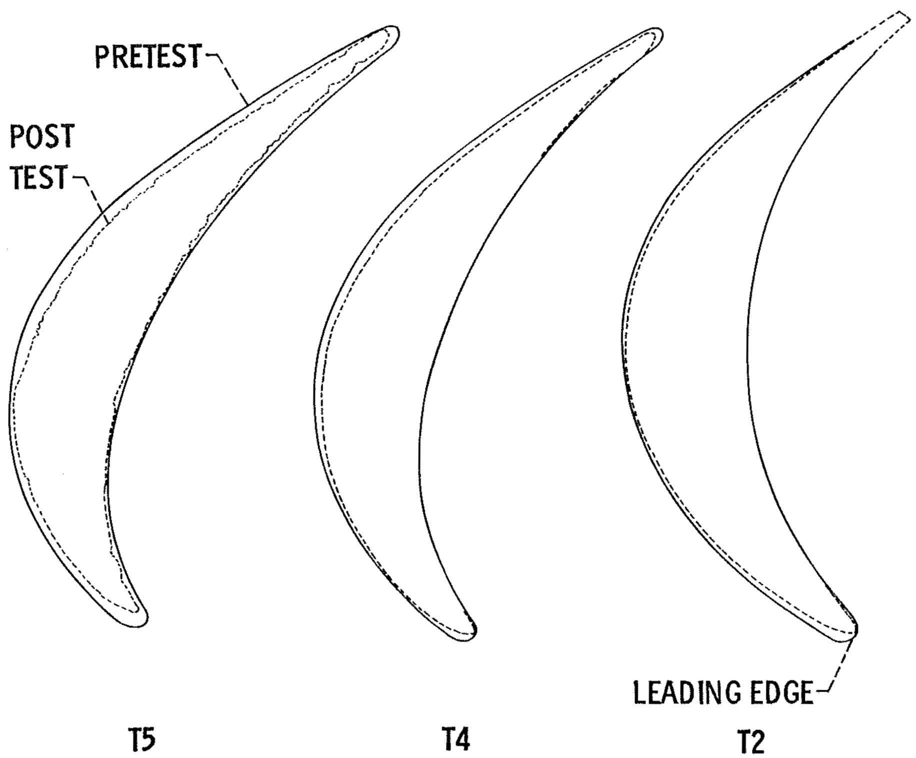


Figure 10. - Pretest and post tests pantascribes of stage three TZM rotor blade AA.

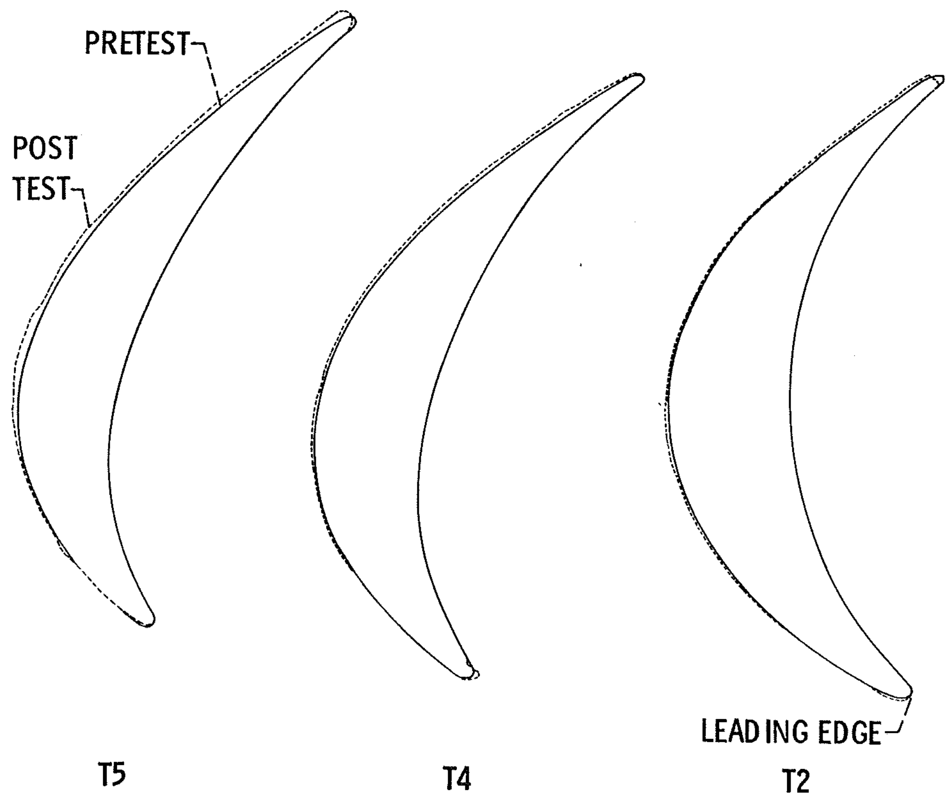


Figure 11. - Pretest and post test pantascribes of stage three Rene 77 rotor blade 45.

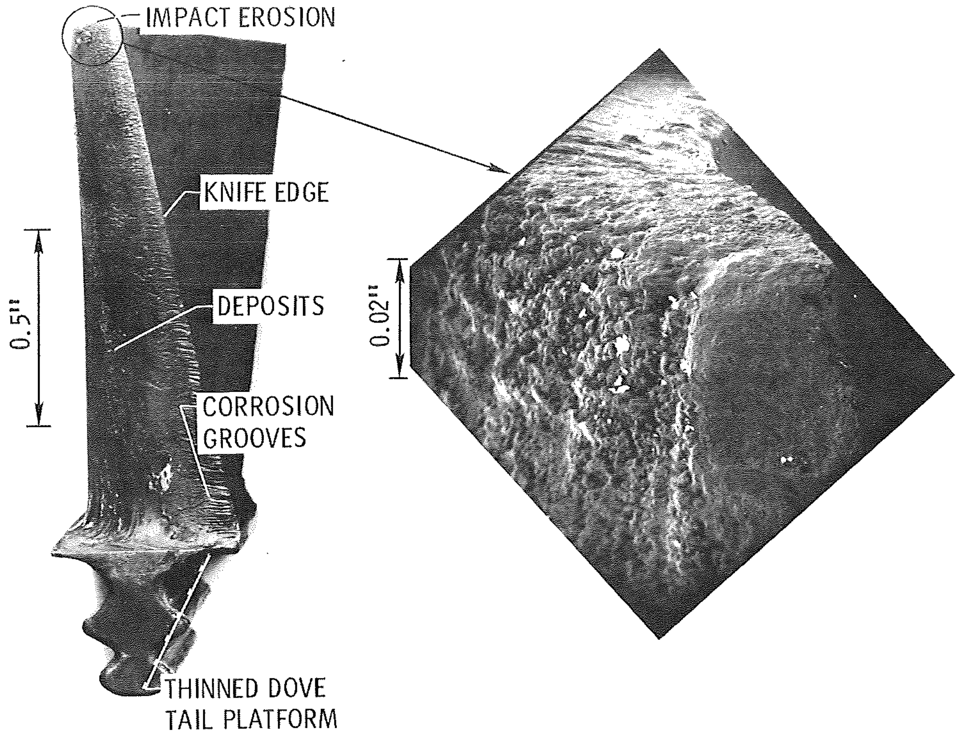


Figure 12. - Mo-TZM CC third stage rotor blade impact erosion damage at tip.

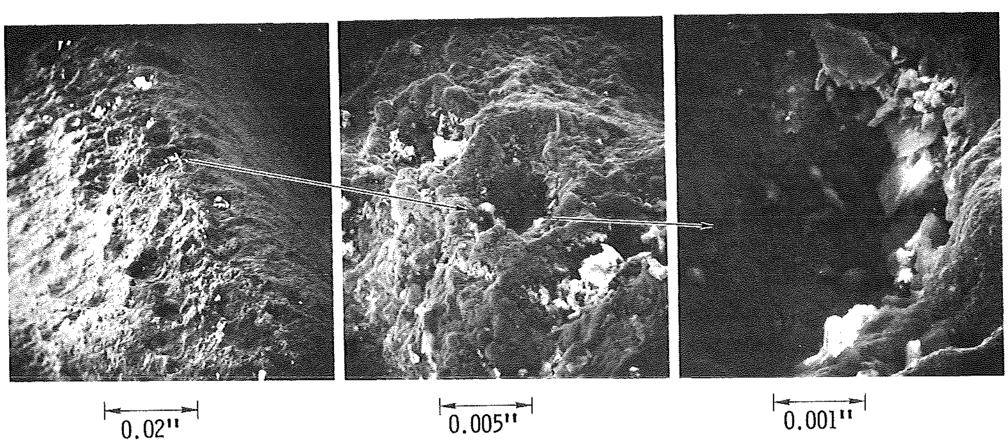


Figure 13. - Close-up of erosion pit at tip of Mo-TZM CC rotor blade.

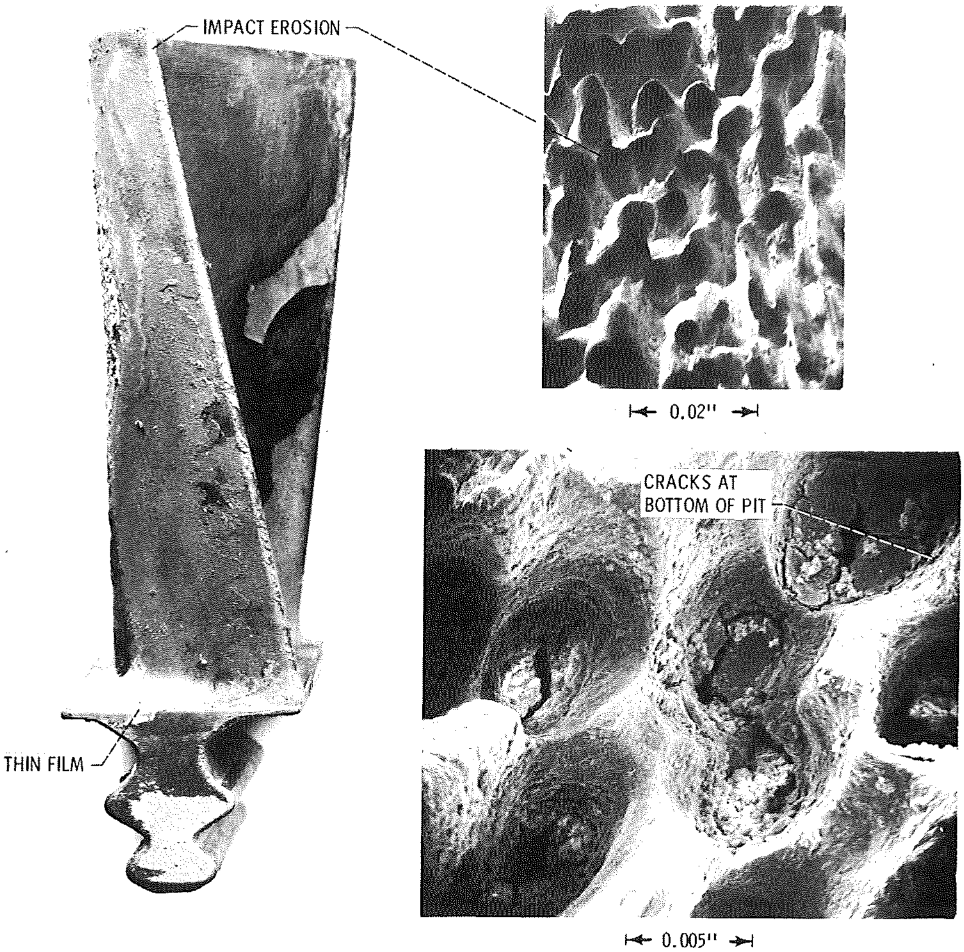


Figure 14. - Impact damage at tip of Rene' 77 blade No. 19.

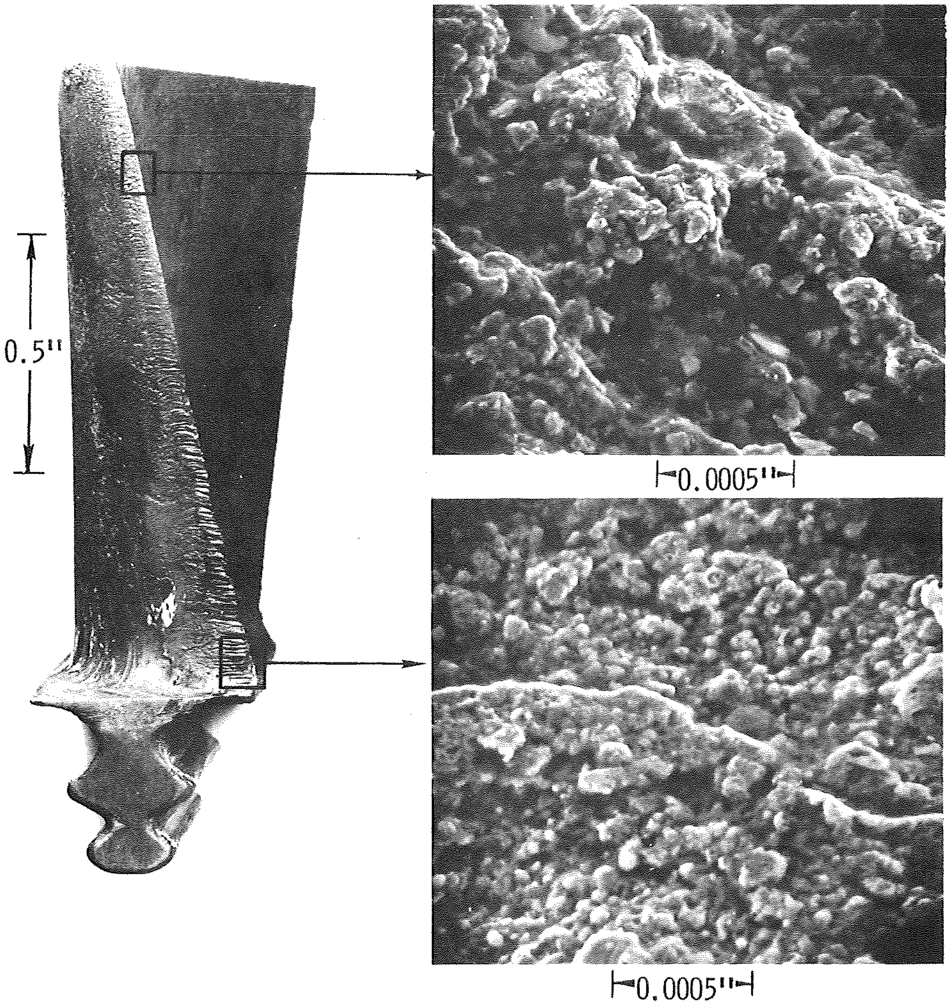


Figure 15. - Mo-TZM CC third stage rotor blade close-up of damage on leading edge convex surface.

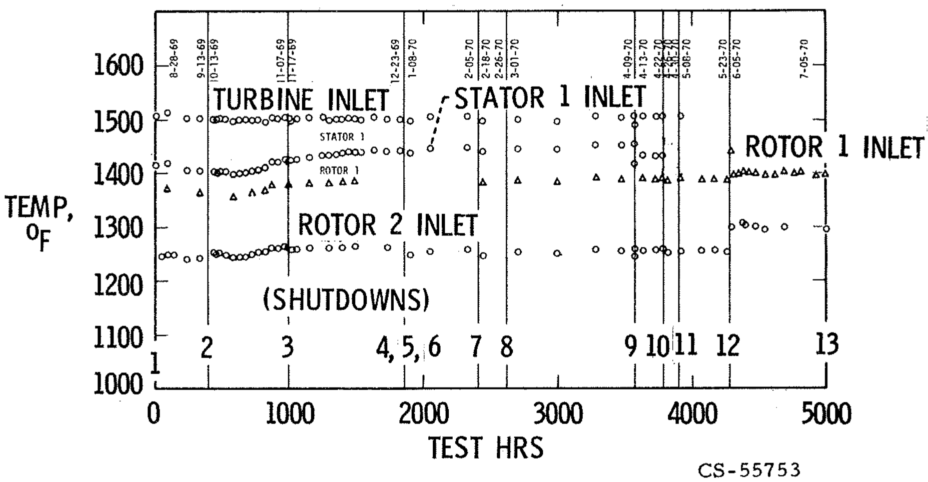


Figure 16. - Variation of temperature within the turbine with endurance time. Turbine inlet temperature, 1500° F; speed, 18 250 rpm.

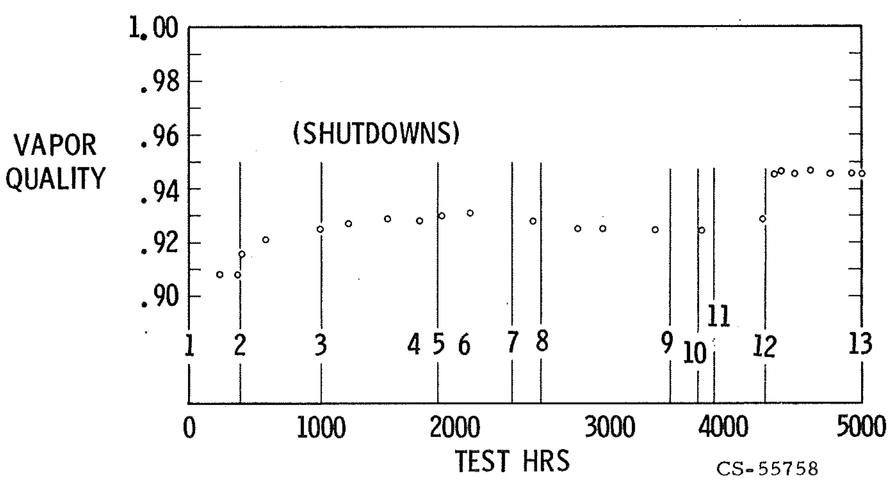
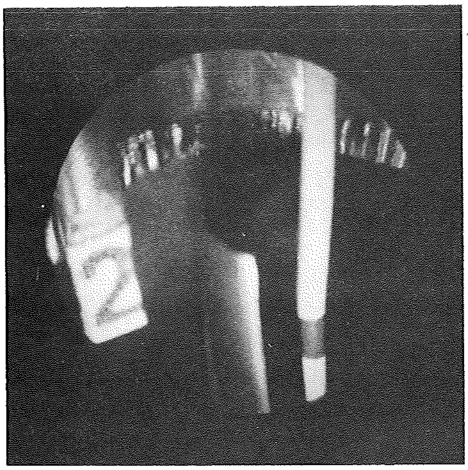
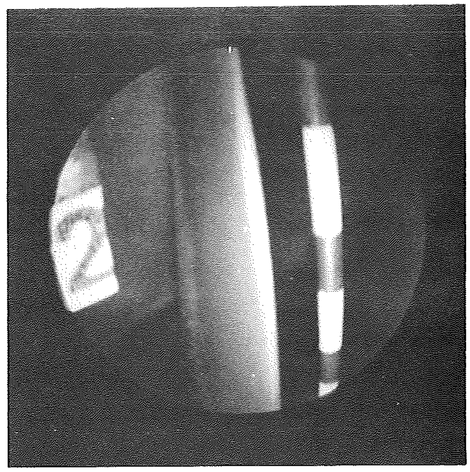


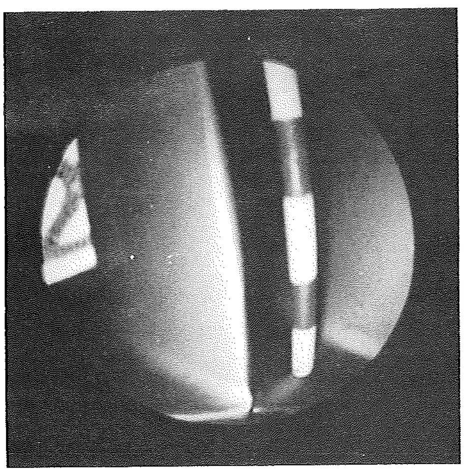
Figure 17. - Variation of third stage inlet vapor quality with endurance time. Turbine inlet temperature, 1500° F; speed, 18 250 rpm.



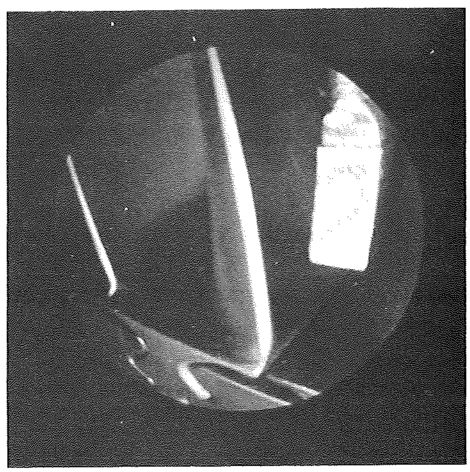
LEADING EDGE



LEADING EDGE



LEADING EDGE



LEADING EDGE, ROTATED

Figure 18. - Pre-test borescope record photographs of stage 3 bucket W (Mo-TZC).

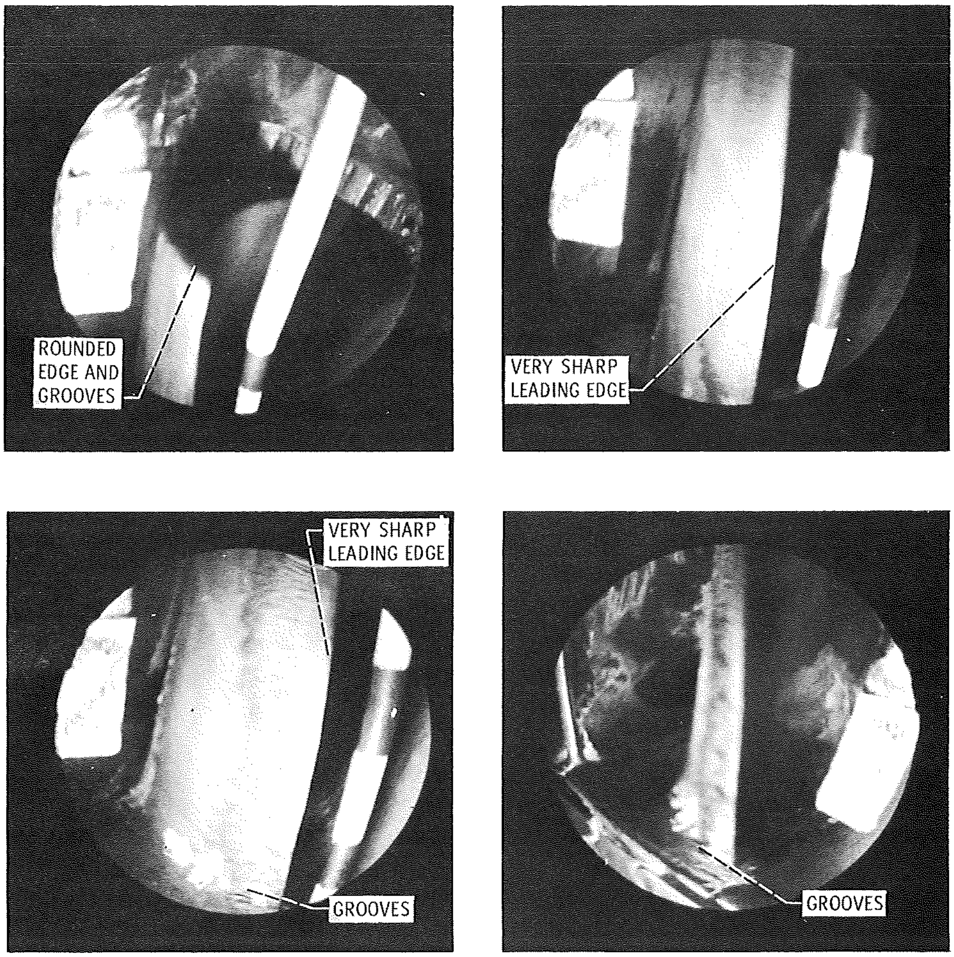
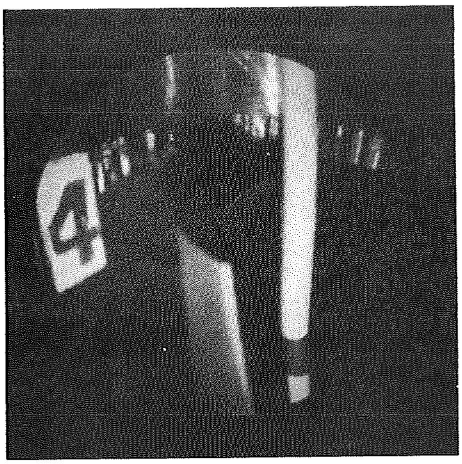
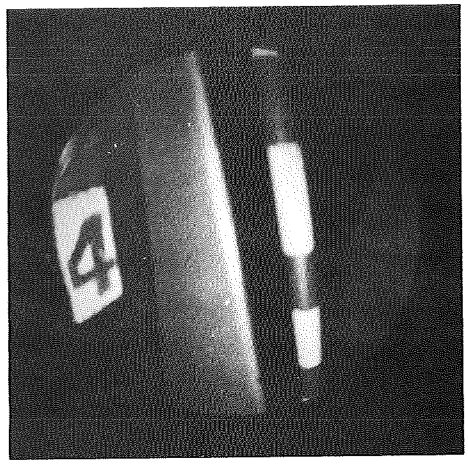


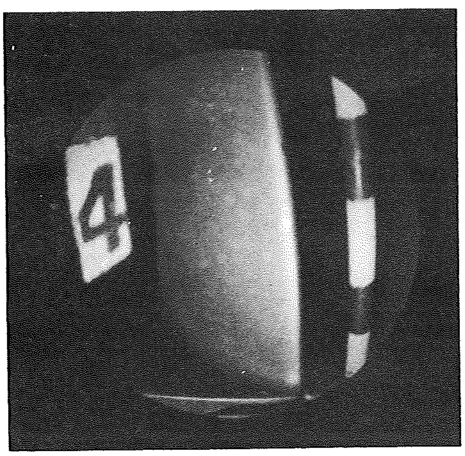
Figure 19. - Boroscope photographs of stage 3 bucket W (Mo-TZc) after 405 endurance hours.



LEADING EDGE



LEADING EDGE



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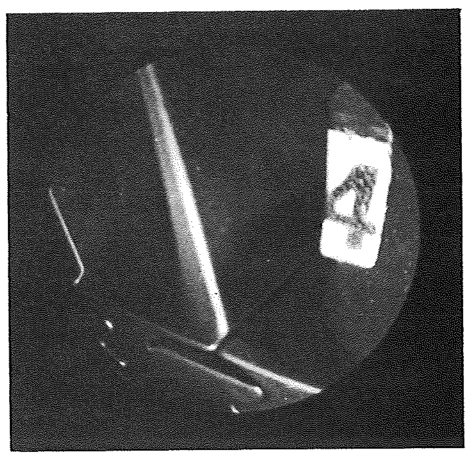
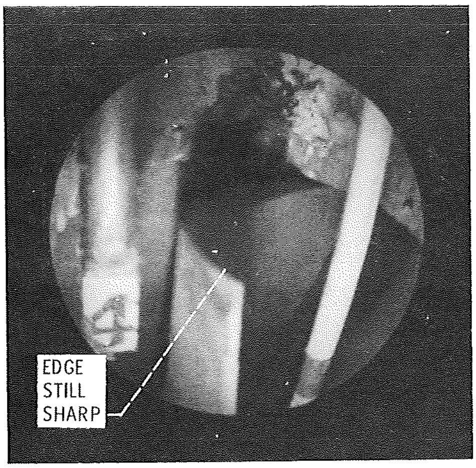


LEADING EDGE, ROTATED

Figure 20. - Pre-test borescope record photographs of stage 3 bucket 71 (René 77).



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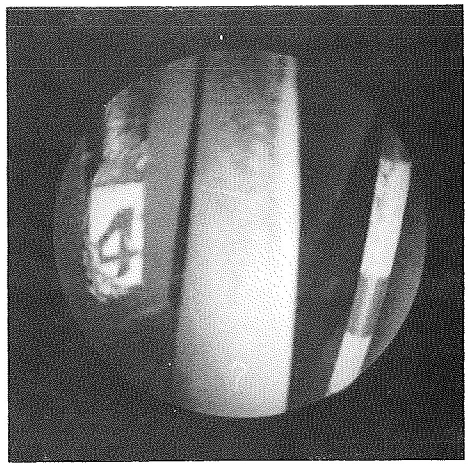

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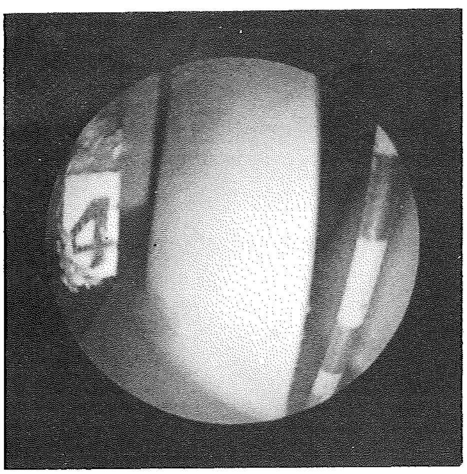

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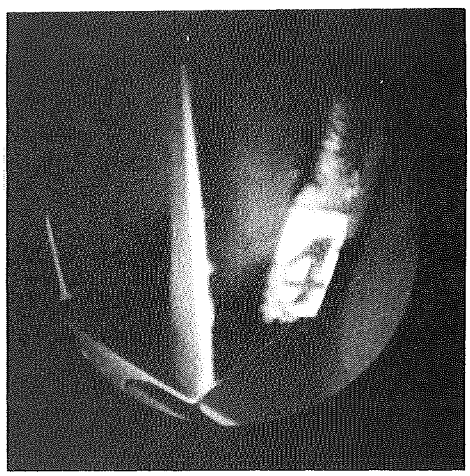

LEADING EDGE, ROTATED

Figure 21. - Boroscope photograph of stage 3 bucket 71 (Rene' 77) after 1865 endurance hours.

E-5919

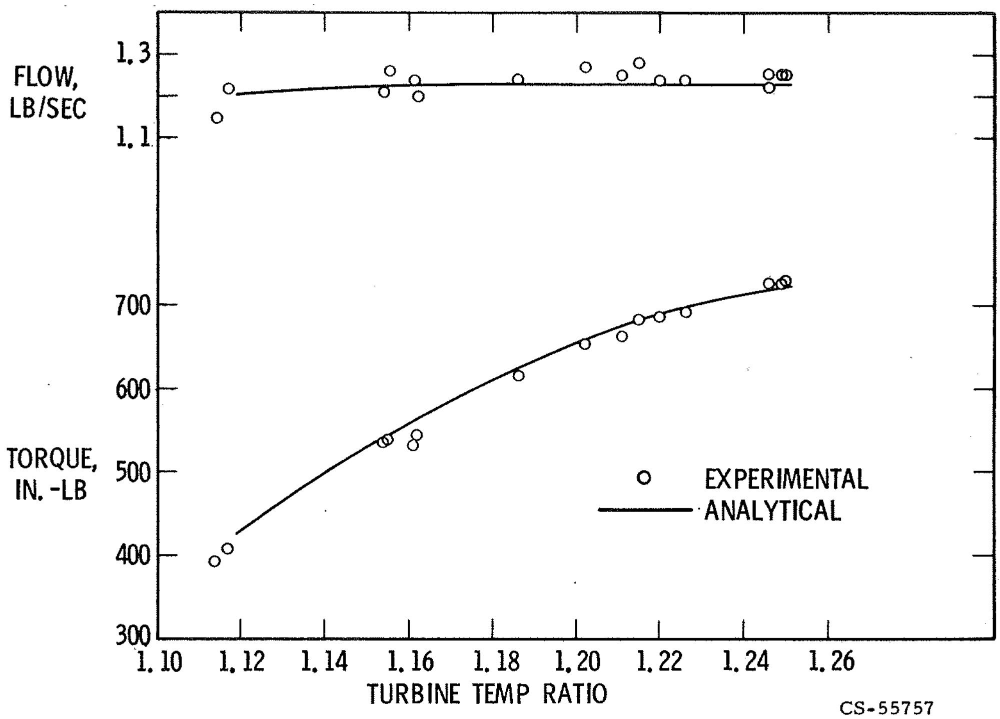

Figure 22. - Comparison of analytical and experimental performance before 5 000-hour test. Turbine inlet temperature, 1450° F; speed, 17 300 rpm.

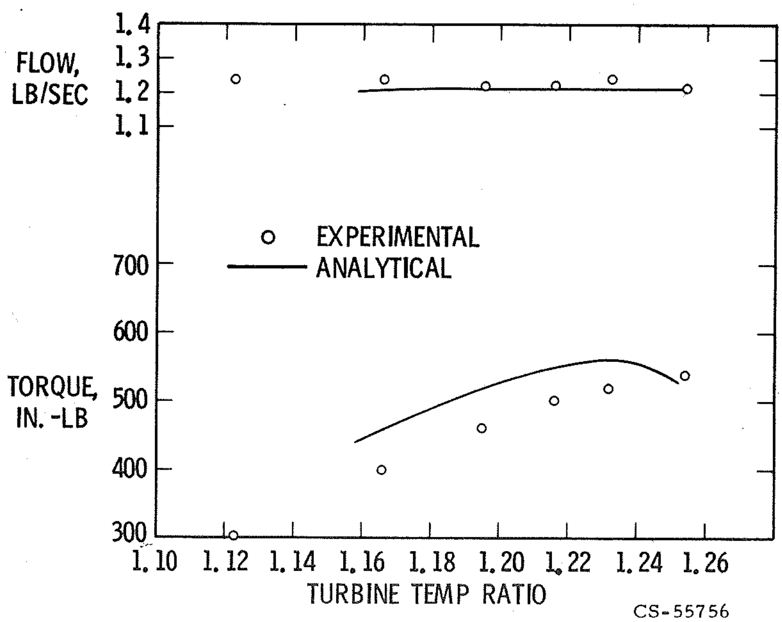

Figure 23. - Comparison of analytical and experimental performance after 5 000-hour test. Turbine inlet temperature, 1450° F; speed, 17 300 rpm.